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BASED ON WEIGHT MINIMIZATION

by

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METHODS OF DESIGNING COOLING CONTROL SURFACES BASED ON WEIGHT MINIMIZATION

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Abstract: This paper introduces the characteristics of cooling control surfaces and, based on analyzing their servovalves, driving devices, air collectors, and load matching, proposes some methods of designing cooling control surfaces based on weight minimization.

Key words: aerodynamic control surfaces, servomechanisms.

1. Characteristics of Cooling Control Surfaces

Cooling control surfaces, with their superiority due to structural simplicity, high reliability, and low cost, enjoy broad applications in tactical missiles. Fig. 1 compares weight/output power among power-driven, hydraulic, and aerodynamic cooling control surfaces (for specified parameters, see Table 1). Of the 15 domestic and foreign control surface models listed in Fig. 1, six are cooling control surfaces. It is clearly seen in Fig. 1 that the weight of cooling control surfaces is lower than for power-driven and hydraulic control surfaces but somewhat higher than gas control surfaces. However,

cooling control surfaces have remarkably higher reliability compared with gas control surfaces. Therefore, cooling control surfaces can increase missile reliability and longevity.

Nevertheless, with the steadily growing firing range of air-to-air missiles, cooling control surfaces are required to operate for a longer time, which leads to the enlargement of air collectors and, eventually, to heavier control surfaces. In response to this situation, it is necessary to create new control modes and to study research and design methods in the hopes of reducing the weight of cooling control surfaces and expanding their breadth of application.

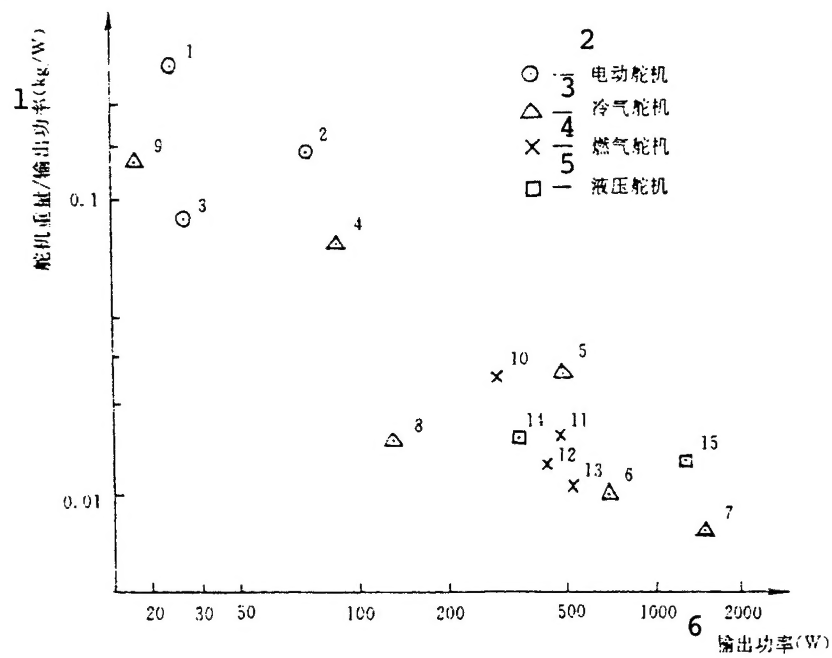

Fig. 1. Comparison of weight among different control surfaces
KEY: 1 - weight/output power of control surfaces (kg/W) 2 - power-driven control surfaces 3 - cooling control surfaces 4 - gas control surfaces 5 - hydraulic control surfaces 6 - output power (W)

TABLE 1. Weight and Output Power Values of Different Control Surfaces

1 序号	2 型号	3 类型	4 舵机重量(kg)	5 最大输出功率(W)	6 重量/功率
1	530	11 电动	6.5	24	0.27
2	550	12 电动	10	68	0.147
3	AQM	13 电动	2.25	26.8	0.084
4	10	14 冷气	6.18	88	0.07
5	Q-2	15 冷气	12	493	0.024
6	60	16 冷气	6.5	677	0.0096
7	80	17 冷气	12	1496	0.008
8	90	18 冷气	2	137	0.015
9	7 倾斜	19 冷气	2.2	17	0.117
10	20#	20 燃气	7.9	304	0.026
11	30#	21 燃气	8	479	0.016
12	50#	22 燃气	6	445	0.0135
13	8 百舌鸟	23 燃气	6.7	524	0.0128
14	9 猎鹰	24 液压	6	370	0.016
15	10 麻雀	25 液压	20.5	1332	0.015

KEY: 1 - serial number 2 - models 3 - types
4 - weight of control surfaces (kg)
5 - maximum output power (W) 6 - weight/power
7 - "Slanting" 8 - Phoenix 9 - "Eagle"
10 - Sparrow 11 - power-driven 12 - power-driven 13 - power-driven 14 - cooling
15 - cooling 16 - cooling 17 - cooling
18 - cooling 19 - cooling 20 - gas
21 - gas 22 - gas 23 - gas 24 - hydraulic
25 - hydraulic

2. Efficiency of Valves

Increasing the efficiency of servovalves and designing the most "gas-sparing" servovalves is the most effective way of reducing weight. Early cooling control surfaces, due to their small power, could only be applied in missiles with a very short operating time, and the servovalves adopted in the control surfaces at that time were simple and inefficient, such as the

nozzle-baffle valves and jet pipe valves. These valves consumed large quantities of gas in the static state (see Fig. 2), which was completely wasted without doing any work.

For better efficiency of nozzle-baffle valves, a quad-nozzle valve (Fig. 3) was developed, which can reduce static-state gas consumption by half (curve d in Fig. 2). In addition to the quad-nozzle valve, a middle-closed switch valve can also remarkably increase efficiency but can work only in the switched state and frequently has to be linearized using a pulse width modulation (PWM) technique. In this working state, its static-state gas consumption is expressed with curve c, i.e., its gas consumption reaches a minimum with an intermediate signal.

An ideal zero open-slot four-way slide valve can attain the highest efficiency because it does not consume gas in the static state unless the control surface is moving. The four-way slide valve is widely used in hydraulic systems. As for the aerodynamic system, it requires a four-way slide valve well sealed in the radial direction due to the very low gas viscosity, yet such a four-way valve can hardly be constructed. The aerodynamic slide valve used now suffers from substantial gas leaks in radial direction and still cannot provide high efficiency (see curve e).

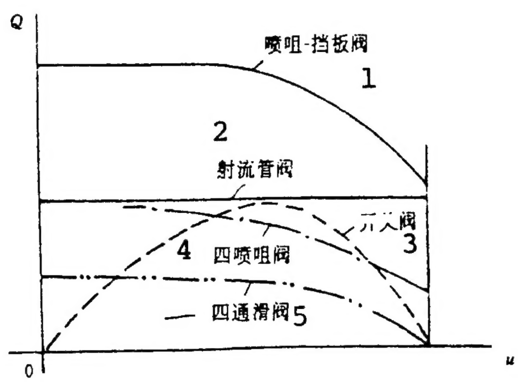

Fig. 2. Static-state gas consumption for various servovalves
KEY: 1 - nozzle-baffle valve 2 - jet pipe valve
3 - switched valve 4 - quad-nozzle valve
5 - four-way slide valve

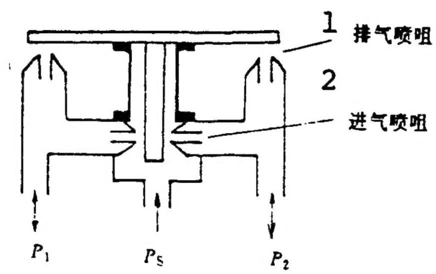

Fig. 3. Working principle of quad-nozzle-baffle valve
KEY: 1 - air discharge nozzle 2 - air collector nozzle

It is possible to produce a middle-closed four-way valve based on four two-position two-way switched valves. Differential control over the four switched valves can be realized through electric circuits. Thus, this kind of valve not only can avoid gas consumption in the static state, but also has the functions of a four-way slide valve. As a result, it can double its efficiency, spare gas, and prolong control surface operating time, or remarkably reduce air collector dimensions and weight.

3. Design of Air Collector

When the power and operating time of a control surface are given, the total required weight of gas can be determined. Once a certain excess amount is taken into account, the total gas storage of the air collector can be calculated. Given a fixed weight of gas, the higher the gas storage pressure, the smaller the air collector dimensions can be. But how does the weight of the air collector change? According to a theoretical analysis[1], given the fixed material strength of the air collector, its weight and outer diameter needed per kg of nitrogen change with gas storage pressure are shown in Fig. 4.

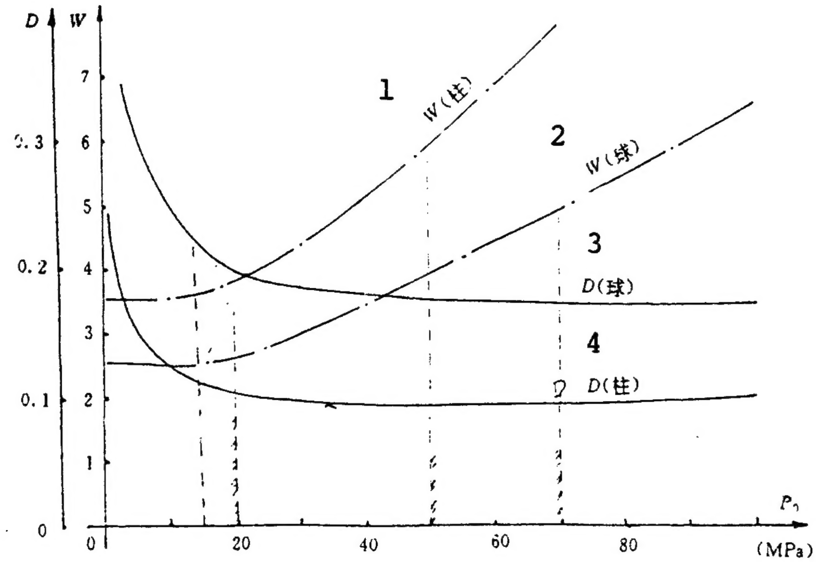

Fig. 4. Relationship between relative weight W and outer diameter D of air collector and gas storage pressure P_0
KEY: 1 - W (cylindrical) 2 - W (spherical)
3 - D (spherical) 4 - D (cylindrical)

Fig. 4 indicates that when $P_0 \leq 20$Mpa, the weight of the air collector remains unchanged but its outer diameter rapidly decreases with increase in P_0. The pressure of civil-oriented air collectors is generally 15Mpa, which allows them to be of small dimensions and light in weight. When $P_0 > 20$Mpa, the weight of the air collector gradually increases while its outer diameter decreases slowly with increase in pressure. When the pressure reaches as high as 50-70Mpa, the outer diameter remains almost unchanged but the weight increases rapidly. Under these conditions, the following two principles can be proposed in selecting a proper gas storage pressure of the air collector:

(1) Principle of minimum weight: the optimal gas storage pressure is P_0=15-20Mpa and

(2) Principle of minimum volume: the optimal gas storage pressure is P_0=50-70Mpa.

Fig. 4 shows the variation curves of spherical and long cylindrical air collectors, which obey the same law. Yet the weight of the cylindrical air collectors is approximately 50% greater than that for the spherical air collectors. Therefore, it would be preferable to use spherical air collectors if structure considerations permit. When cylindrical air collectors are necessary, their length-diameter ratio should be designed larger (i.e., in a thin and long shape), generally more than 5. In this case, the weight of such collectors will be lighter than that of the thick and short collectors. If the thick and short air collectors must be used owing to structural restrictions, then they should be designed hemispherical at both ends, and their wall thickness should be smaller than that of the cylindrical segment (half of its size). The connecting section between the two segments should be gradually transitional so that the pressure will be less concentrated in individual areas[1].

The operating pressure of the control surface P_s also has a remarkable effect on the gas storage pressure. In operation, when the air collector discharges gas and the pressure falls to below the operating pressure, it loses its effect because the residual gas is useless. When P_s is fixed, the higher the P_0, the less the residual gas. The curves shown in Fig. 5 are derived from an analysis of the weight of the air collector with its effective gas storage regarded as standard. Under each given operating pressure P_s, there is an optimal gas storage pressure P_{01}, during which the weight of the air collector is the smallest.

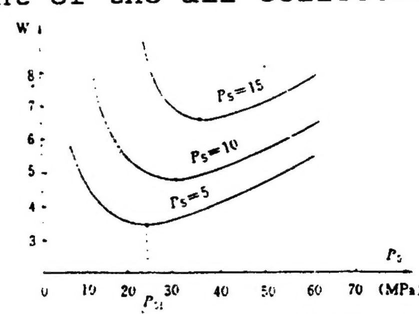

Fig. 5. Effect of control surface operating pressure P_s on air collector weight

Indeed, the weight minimum does not necessarily correspond to a rational volume and because of this, the air collector may not be suitable for installation in the missile. If this situation occurs, one possible solution is to reduce the volume by raising pressure at the expense of weight. It is also possible to adjust the air collector dimensions by changing the operating pressure of the control surface operating pressure. This will be discussed later.

4. Design of Driving Device

Since the weight of a driving device accounts for more than one-third of the total weight of the control surface, a reasonable design of a driving device plays an important part in reducing the weight of the control surface.

In a large-diameter missile, the four control surfaces are generally driven separately, particularly when the control surface is mounted around the jet pipe at the tail. In this case, a double-acting driving tube is a general choice, on which a servovalve is fixed. This structure is light in weight because it has no excess metal. With this structure, the control surface axis bears only the small output force generated by the pressure difference in the air cylinder and therefore, it can be made smaller. However, this structure is not compact enough because it has a large vertical dimension and needs a special gas supply pipe. Still, it is used wherever it is permitted, such as AA-1, AA11 and CAM-2 only because it can reduce weight.

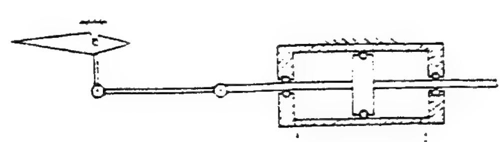

Fig. 6. Double-acting driving tube

An integral driving device (Fig. 7) is basically used in small-diameter missiles and especially in canard-layout missiles. In this case, four (or eight) air cylinders are mounted on the end face of an entire body, each with two air cylinders constituting a push-pull differential driving device to push a pair (or one) of control surface faces to deflect. This structure is advantageously compact and reliable as air flow paths can be formulated by making holes in the body without needing connecting pipes. While its disadvantage is its heavy weight because of large amounts of surplus metal in the body, and it requires a thick control surface axis to bear a large force in balancing two differential piston forces. The following description is devoted to further details in designing the structure shown in Fig. 7. Using the following method to select parameters can make the weight as light as possible.

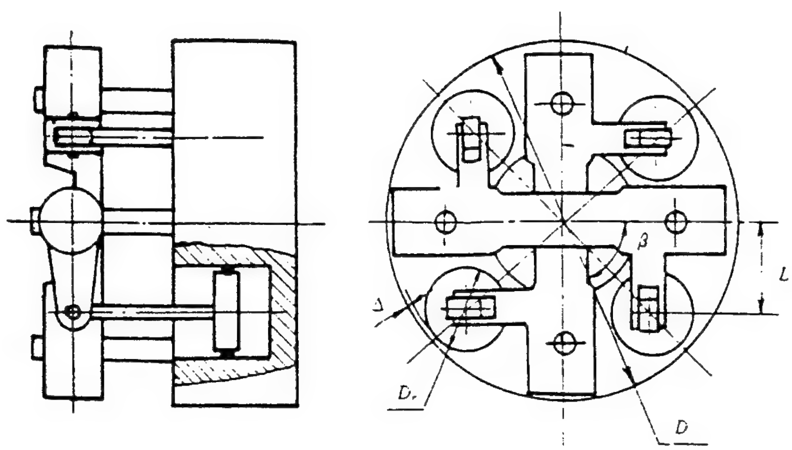

Fig. 7. Integral control-surface driving device

When the four air cylinders are set up on the end face of the body, the following expression can be derived based on the geometric relationship:

$$\frac{A_R L}{\frac{\pi}{8} D_0^3 \sin\beta} = m_r^2(1 - m_r) \tag{1}$$

where $m_r = D_r/D_0$ is relative diameter of air cylinder;

$D_0 = D - 2\Delta$

$A_R = (\pi/4)D$;

the implications of other symbols are explained in Fig. 7.

Eq. (1) indicates the relationship between the discharge capacity of driving device $A_R L$ and the diameter of air cylinder as shown in Fig. 8, which reaches a maximum value when $m_r=2/3$. This actually cannot be realized structurally. The permitted maximum value in reality is $m_r=0.4$ point. At this moment,

$$\frac{A_R L}{\frac{\pi}{8} D_0^3 \sin\beta} = 0.1 \tag{2}$$

if $\beta=40^0$, the following can be derived:

$$A_R L = 0.028 D^3 \tag{3}$$

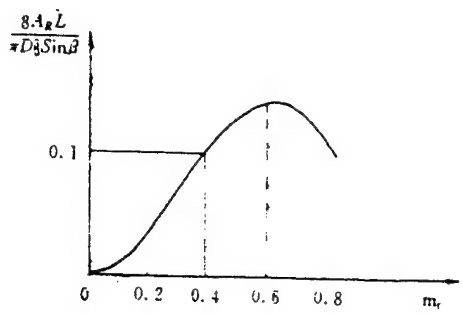

Fig. 8. Relationship between relative discharge capacity and relative diameter of air cylinder

Eq. (3) provides the maximum discharge capacity derived while assuming a fixed body diameter. It is necessary to arrange four air cylinders of the largest possible size on the limited end face of the body to acquire a large $A_R L$ value. Under a fixed output moment, the operating pressure of the control surface can be decreased and the weight of the air collector can be reduced. Fig. 9 shows the variation curves of body and air collector weight with m_r. When $m_r=0.3$, the body reaches a maximum weight, and the weight of the air collector decreases with increase in m_r. If the integral weight of the air collector and body is taken into account, it is fairly reasonable to select $m_r=0.3$-0.4.

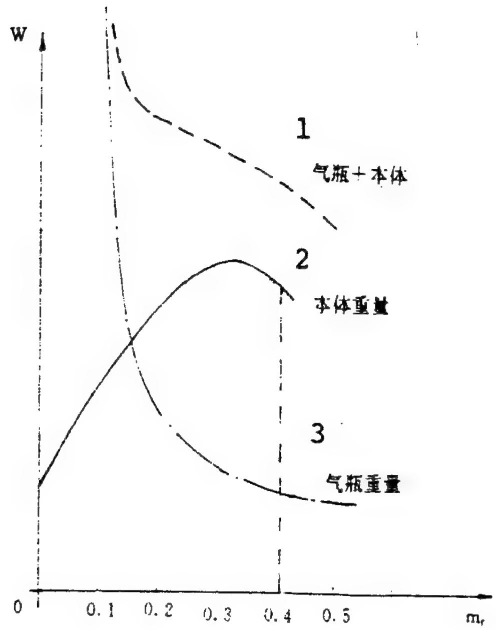

Fig. 9. Variation of body and air collector weight with m_r
KEY: 1 - air collector + body 2 - body weight
3 - air collector weight

There is a diversity of driving modes. Selecting a rational structure in accordance with specific conditions is the most effective means in reducing weight. Take the driving mode in Fig. 10 as example, a discharge capacity 50% higher than that of the structure in Fig. 7 can be obtained in the same space, which can then reduce the control surface operating pressure (or increase the output moment).

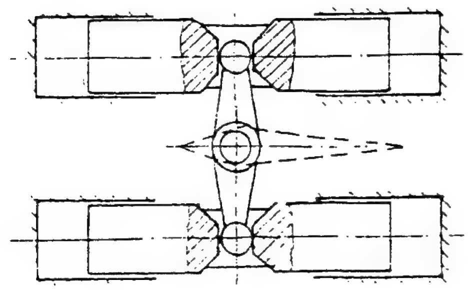

Fig. 10. Integral double-acting driving device

5. Load Matching

Load matching involves matching between the control surface output power and the power required in controlling the control surface movement. In designing a servosystem, it is necessary to ensure that the system can effectively drive the load in accordance with a required law, and that it does not have too much excess power.

In designing a servosystem, the load is frequently described with its track. When the control surface is in a sinusoidal movement at a particular frequency and amplitude, the load pressure and load flux of an aerodynamic control surface can be expressed in the following equation[3]:

$$P_L=P_{L0}\ \sin(\omega t+\omega)+P_f \tag{3}$$

$$Q_L=Q_{L0}[\cos\omega t+d\cos(\omega t+\psi)] \tag{4}$$

where $P_{L0}=(a\delta_0/A_RL)$ is the amplitude value of load pressure;

$Q_{L0}=A_RL\omega\delta_0$ is the amplitude value of load flux;

$\sin\psi=B\omega/a$;

$a=\sqrt{(K_L-T\omega^2)^2+(B\omega)^2}$

$P_f=M_f/A_RL$;

$d=aV_0/2\beta(A_RL)^2$;

M_f is frictional moment;

K_L is hinge moment coefficient;

B is viscous friction coefficient;

J is load-turning inertia

β is gas elastic modulus; in an adiabatic process, β=kP, where k is adiabatic index and P is air cylinder pressure

V_0 is air cylinder median volume.

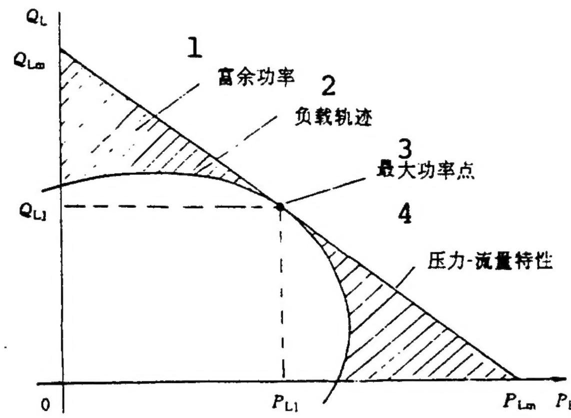

Fig. 11. Load track matched with load pressure-flux properties of valve
KEY: 1 - surplus power 2 - load track 3 - maximum power point 4 - pressure-flux properties

The load track marked in Eqs. (3) and (4) is an ellipse in the P_L-Q_L plane as shown in Fig. 11. If the maximum load pressure-flux properties curve of the servovalve can enclose this load track, it indicates that the control surface has sufficient power. The area between the two curves stand for the degree of power surplus. This area is hopefully as small as possible for the sake of power sparing. The general practice is to overlap the maximum power point on the load pressure-flux properties curve with the maximum power point on the load track and to make the two lines tangential to each other. When the valve properties are a downward slanting straight line, an optimal matching can be obtained with a minimum surplus area.

The above-mentioned matching method can only represent a typical work state of a control surface. In actual flight,

however, the control surface motion law varies greatly with different trajectories. Fig. 12 shows the load track of a particular trajectory, derived from a digital simulation. It can be seen distinctly that this track is extremely complicated and can hardly be defined as an elliptical track.

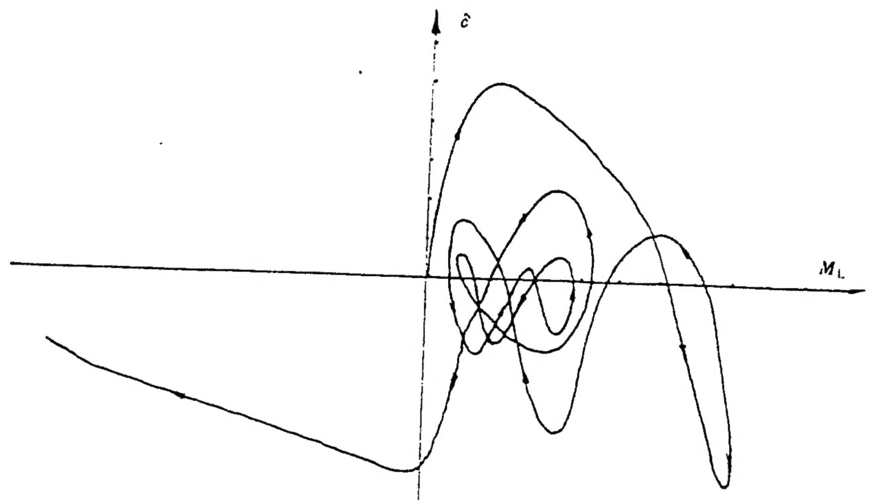

Fig. 12. Control surface load track along a particular trajectory

Load matching can be conducted in the following manner: First, perform a numerical simulation over the control system to acquire load tracks along different trajectories. Single out the maximum power points, maximum moment points, and maximum angular velocity points on these tracks and mark them in the δ-M_L plane. These points are distributed in a particular area of the plane (see Fig. 13). Only if it is determined that the mechanical properties of the control surface enclose this area, can the control surface meet the power requirements. It is to be noted that the boundary of this area is not "distinct" but blurred, which should be processed based on probability. For instance, it can be selected as 95%. It is reasonable to determine the control surface power when the mechanical properties enclose this area alone. If individual points with extremely small probability are also enclosed (such as N point in the figure),

the control surface power will be over large and its weight will be increased for naught.

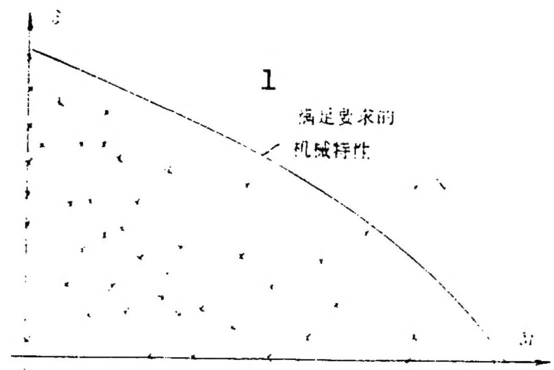

Fig. 13. Determination of control surface mechanical properties based on actual load distribution
KEY: 1 - mechanical properties satisfying the requirements

6. Conclusions

To summarize the foregoing description, there are several steps in designing the cooling control surfaces with weight minimum, namely:

(1) Select the most gas-sparing servovalve;

(2) Select a rational driving device mode;

(3) Conduct an optimal load-matching in accordance with the overall technical requirements so as to determine the load pressure-flux properties of the servovalve (or the mechanical properties of the control surface);

(4) Design the air collectors under the condition of weight minimum;

(5) Conduct system integration so that the control surface can achieve the required speed, stability and static state

precision.

Following the foregoing steps, it will be possible to design cooling control surfaces with the lightest weight.

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